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14. ABSTRACT

Visualizations of high--?order finite element results that do not respect the a priori knowledge of how the data were produced and which do not provide a quantification of the visual error produced undermine the scientific process. The goals of this effort are to define, investigate, and address the technical obstacles inherent in visualization of data derived from high--order numerical methods and to provide robust and efficient algorithms to the high--order simulation community.

15. SUBJECT TERMS

Cut-Plane/Surface and Contouring of High-Order Data and Volume Rendering Visualization of High-Order Methods

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Report Title

Visualization of High-Order Finite Element Methods
Final Report

Proposal Number W911NF-08-1-0517

Professor Robert M. Kirby, School of Computing, University of Utah and Mr. Robert Haimes, Department of Aeronautics & Astronautics Massachusetts Institute of Technology

ABSTRACT

Visualizations of high--?order finite element results that do not respect the a priori knowledge of how the data were produced and which do not provide a quantification of the visual error produced undermine the scientific process. The goals of this effort are to define, investigate, and address the technical obstacles inherent in visualization of data derived from high--order numerical methods and to provide robust and efficient algorithms to the high--order simulation community.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations:

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Blake Nelson	1.00	
Tobias Martin	0.50	
FTE Equivalent:	**1.50**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Robert M. Kirby	0.63	No
FTE Equivalent:	**0.63**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME
Blake Nelson

Total Number: 1

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

1 a. Robert Haimes

1 b. MIT Department of Aeronautics and Ast
77 Massachusetts Avenue 33-207
Cambridge MA 02139

Sub Contractor Numbers (c):

Patent Clause Number (d-1):

Patent Date (d-2):

Work Description (e): Accomplish stress-testing of the new ElVis system using domain-speci□c engineering datasets

Sub Contract Award Date (f-1): 9/26/2008 12:00:00AM

Sub Contract Est Completion Date(f-2): 9/25/2012 12:00:00AM

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

Visualization of High-Order Finite Element Methods
Final Report
Proposal Number W911NF-08-1-0517

Professor Robert M. Kirby, School of Computing, University of Utah and Mr. Robert Haimes, Department of Aeronautics & Astronautics Massachusetts Institute of Technology

Objective

Visualizations of high-order finite element results that do not respect the a priori knowledge of how the data were produced and which do not provide a quantification of the visual error produced undermine the scientific process. The goals of this effort are to define, investigate, and address the technical obstacles inherent in visualization of data derived from high-order numerical methods and to provide robust and efficient algorithms to the high-order simulation community.

Approach

The thesis of this proposal that in turn drives our approach is that a visualization methodology for high-order finite element data that exploits the high-order nature of the data in its native form provides a visual representation that introduces no (or quantifiable) approximation error due to the visualization technique. There are many possible reasons why this thesis is beneficial to the high-order finite element community. The proposed visualization techniques (1) use the data in its native form, hence helping to allay the computational scientists' concern that information is being lost when current visualization techniques are applied; (2) allow the computational scientists to focus their efforts on elimination of other sources of error (modeling errors, numerical (simulation) errors, etc.) because it eliminates visualization approximation error; and (3) provide "ground truth" images to which low-order visualization techniques applied to high-order finite element data can be compared.

Scientific Opportunities and Barriers

Many current scientific visualization techniques applied to higher-order solutions are inadequate when used for knowledge extraction and assistance in reducing the error budget because they transform high-order data to low-order representations for visualization purposes – a process which in and of itself adds "visualization error" to the error budget. The scientist is currently burdened with determining whether or not an anomaly found in an image generated by a visualization technique is from the modeling and discretization assumptions made as part of the simulation or as part of the visualization technique. In most cases that burden is high. In this proposed work we will examine several common scientific visualization techniques used for depicting scalar field values from the results of high-order finite element (continuous Galerkin and discontinuous Galerkin) simulations. We propose to create "high-order cognizant" visualization algorithms and strategies for high-order continuous and discontinuous data on planar and curved elements.

Significance

The proposed research impacts three areas: the mathematical sciences, the computer sciences, and the interdisciplinary bridge lying between these two areas. The high-order finite element community will benefit from this effort through the proposed development of algorithms which accurately and efficiently render simulation results. The visualization community will benefit through the exposure to the high-order finite element community and, in particular, the numerical methods prevalently found there. Other current projects funded by ARO's program in computational mathematics which use high-order finite elements will find immediate utility of the algorithms and implementations discussed herein (e.g. projects funded at Brown University, RPI, etc.).

Accomplishments

Over the life of the current grant, we have focused on the developed of algorithms for the visualization of high-order elements. These algorithms have been implemented in our "Element Visualizer" ElVis, which is available as an open-source tool. As part of our research, we focused on the following:

- Cut-Plane/Surface and Contouring of High-Order Data,
- Volume Rendering Visualization of High-Order Methods, and
- Verifiability of our software (and of visualization algorithms in general).

The following publications came as a consequence of the funding provided:

- E. Cohen, T. Martin, R.M. Kirby, T. Lyche and R.F. Riesenfeld, "Analysis-aware Modeling: Understanding Quality Considerations in Modeling for Isogeometric Analysis", *Computer Methods in Applied Mechanics and Engineering*, Vol. 199, Issues 5-8, pages 334-356, 2010.

- Blake Nelson, Robert Haimes and Robert M. Kirby, "GPU-Based Interactive Cut-Surface Extraction From High-Order Finite Element Fields", *IEEE Transactions on Visualization and Computer Graphics (IEEE Visualization Issue)*, Vol. 17, No. 12, pages 1803-1811, 2011.

- Tobias Martin, Elaine Cohen and Robert M. Kirby, "Mixed-Element Volume Completion for NURBS Surfaces", *Computers & Graphics*, Vol. 36, Issue 5, pages 548-554, 2012.

- Tiago Etiene, L. Gustavo Nonato, Carlos Scheidegger, Julien Tierny, Thomas J. Peters, Valerio Pascucci, Robert M. Kirby and Claudio T. Silva, "Topology Verification for Isosurface Extraction", *IEEE Transactions on Visualization and Computer Graphics*, Vol. 18, No. 6, pages 952-965, 2012.

- E. Cohen, T. Martin, R.M. Kirby, T. Lyche and R.F. Riesenfeld, "Analysis-aware Modeling: Understanding Quality Considerations in Modeling for Isogeometric Analysis", *Computer Methods in Applied Mechanics and Engineering*, Vol. 199, Issues 5-8, pages 334-356, 2010.

- Tobias Martin, Elaine Cohen and Robert M. Kirby, "Direct Isosurface Visualization of Hex-Based High-Order Geometry and Attribute Representations", *IEEE Transactions on Visualization and Computer Graphics*, Vol. 18, No. 5, pages 753-766, 2012.

- Blake Nelson, Eric Liu, Robert M. Kirby, and Robert Haimes, "ElVis: A System for the Accurate and Interactive Visualization of High-Order Finite Element Solutions", Accepted upon Revision to IEEE Visualization Conference, 2012.

- Blake Nelson, Robert M. Kirby, and Steven Parker, "Optimal Expression Evaluation Through the Use of Expression Templates When Evaluating Dense Linear Algebra Operators", Under Review, *ACM Transactions on Mathematical Software*, 2012.

- Blake Nelson, Robert M. Kirby, and Robert Haimes, "GPU-Based Interactive Volume Visualization From High-Order Finite Element Fields", In Preparation for *IEEE Transactions on Visualization and Computer Graphics*, 2012.

Software Release
ElVis Version 1: http://www.sci.utah.edu/software/546-elvis.html

Personnel
- Professor Robert M. Kirby – Utah
- Mr. Bob Haimes – MIT
- Dr. Blake Nelson – Utah (earned PhD while being funded on this grant)
- Dr. Tobias Martin – Utah (partially funded for his contribution to the ray-tracing work on high-order spline-based fields)

Collaborations and Leveraged Funding

- Collaborated with Professor Claudio Silva, Formally of School of Computing, University of Utah, and now at the Department of Computer Science, NYU-Poly, on the "Verifiable Visualization" work.

- Collaborated with Professor Elaine Cohen, School of Computing, University of Utah.

- Collaboration with Professor Jennifer Ryan, Delft Institute of Applied Mathematics, Delft University of Technology, The Netherlands.

Conclusions

Visualization is often employed as part of the simulation science pipeline. It is the lens through which scientists often examine their data for deriving new science, and is the lens used to view modeling and discretization interactions within their simulations. As such, visualization techniques need to be designed not only to elucidate the features or phenomena of interest within the data, but also to be compatible and complementary with the type and means of generating the data. One such category of simulation data, high-order finite element methods (also known as spectral/*hp* element methods) using either the continuous Galerkin or discontinuous Galerkin formulation, has reached a level of sophistication such that they are now commonly applied to a diverse set of real-life engineering problems. Visualizations of high-order finite element results that do not respect the *a priori* knowledge of how the data were produced and which do not provide a quantification of the visual error produced may undermine the scientific process as isolating where errors and assumptions are introduced into the process is critical.

Technology Transfer

None to report at this time.

Future Plans

We are currently in the process of exploring stress-testing of the ElVis framework on real application data. A Version 1 Release of the software has been made to the community, and we are now accepting user feedback which will be used in the future updates of the Software. Our next research goal is to incorporate features for visualizing high-order discontinuous Galerkin datasets.